Exp Brain Res (2013) 229:533–543
DOI 10.1007/s00221-013-3615-0

RESEARCH ARTICLE

Outsider interference: no role for motor lateralization in determining the strength of avoidance responses during reaching

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Received: 27 November 2012 / Accepted: 10 June 2013 / Published online: 29 June 2013

Abstract When reaches are performed toward target objects, the presence of other non-target objects influences kinematic parameters of the reach. A typical observation has been that non-targets positioned ipsilaterally to the acting limb interfere more with the trajectory of the hand than contralateral non-targets. Here, we investigate whether this effect is mediated by motor lateralization or by the relative positioning of the objects with reference to the acting limb. Participants were asked to perform reaches toward physical target objects with their preferred or non-preferred hands while physical non-targets were present in different possible positions in the workspace. We tested both left-handers and right-handers. Our results show that a participant's handedness does not influence reaching behavior in an obstacle avoidance paradigm. Furthermore, no statistically significant differences between the use of the preferred and non-preferred hand were observed on the kinematic parameters of the reaches. We found evidence that non-targets positioned on the outside of the reaching limb influenced the reaching behavior more strongly than non-targets on the inside. Moreover, the type of movement also appeared to play a role, as reaches that crossed the workspace had a stronger effect on avoidance behavior than reaches that were 'uncrossed.' We interpret these results as support for the hypothesis that the avoidance response is determined by keeping a preferred distance between the acting limb in all stages of its reach toward the target and the non-target position. This process is not biased by hand dominance or the hand preference of the actor.

Keywords Obstacle avoidance · Human · Reaching · Planning · Visuomotor control

Introduction

During everyday activities, people often reach for specific objects in cluttered environments in order to manipulate them. Our ability to correctly select a target from many objects to execute a reach-to-grasp movement is one of the key features in human motor planning. We also specify reaches toward objects to occur with a very low probability of colliding with other objects. Research into these skills has shown that non-target objects have an effect on the spatiotemporal characteristics of hand trajectory (Castiello 1996; Chapman and Goodale 2008; Menger et al. 2012; Mon-Williams et al. 2001; Tipper et al. 1997; Tresilian 1998; Welsh 2011) and that these effects are mediated by an intact dorsal stream (Rice et al. 2006; Schindler et al. 2004; Striemer et al. 2009). Whether these effects were caused by biases during target selection or were caused by the specification of the action (so that non-target objects were avoided) has been difficult to determine for a given situation. Recently, however, an account has been put forward that unifies both problems (Cisek and Kalaska 2010). Action specification and action selection were theorized as neural processes that run in parallel and in the same or similar substrates. Therefore, as attentional allocation and movement planning are closely related, effects reported might not be uniquely attributable to either attentional allocation or movement planning.

Keeping this in mind, we would like to point out that in the majority of studies, there was a difference in magnitude between the effects observed for movement trajectories with ipsilateral non-target objects compared to contralateral

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non-target objects. Specifically, ipsilateral non-targets caused more deviation of the reaching trajectory than contralateral non-targets (Chapman and Goodale 2008; Dean and Bruwer 1994; Meegan and Tipper 1999, 1998; Menger et al. 2012; Mon-Williams et al. 2001; Pratt and Abrams 1994; Tipper et al. 1992). Whether this finding was explained better by the claims that contralateral non-targets were either less 'distracting' or 'obstructing' than ipsilateral non-targets is a futile exercise if one assumes the processes to be the same. However, one outstanding point remains: in both the obstacle avoidance and distractor interference literature, a typical experiment reports an asymmetry between ipsilateral and contralateral non-targets. That is, reach-to-point or reach-to-grasp movements that were made with the right hand by right-handers differed when distracting or obstructing objects were ipsilaterally or contralaterally placed between the starting location and the target location.[1] Simply put, when the right hand was used, objects placed on the right side of the workspace were on the *outside* of the reaching hand and gave rise to larger interference effects or avoidance responses, whereas objects placed on the left side were on the inside of the reaching hand and led to smaller or negligible interference effects or avoidance responses.

The aim of the current study was to investigate the observed differences in magnitude of effects associated with ipsilateral and contralateral non-targets (see, e.g., Chapman and Goodale 2008). We propose two possible explanations for these differences: ipsilateral non-targets potentially obstruct the movement of the lower arm, whereas contralateral non-targets cannot (i), or ipsilateral non-targets affected reaching behavior more strongly because right-handers employing their dominant hand were tested, i.e., because of motor lateralization (ii). In previous experiments, participants only used their preferred right hand and arm to execute the task which makes it impossible to disentangle these effects. Our aim was to test both left- and right-handed participants using their preferred and non-preferred hand to reach and grasp a target with non-target present either ipsi- or contralaterally to the reaching hand. In the following sections, the two alternative hypotheses will be discussed in detail:

(i) Contralateral non-targets caused less deviation than ipsilateral ones because, during normal reach-to-grasp movement execution, the lower arm would never occupy the same space as the contralateral non-target, whereas the lower arm could have knocked over the ipsilateral non-target more readily. This was due to the constraint on the movement imposed by the elbow joint, which, although it allowed the extension of the arm to bridge the distance from starting position toward a target object, also automatically brought the lower arm closer to an ipsilateral non-target. The contralateral non-target was never on the outside of the reaching arm and therefore never in the direction the lower arm travelled when the elbow was extended. As such, the contralateral non-targets could never obstruct the movement in the way ipsilateral non-targets did. If, as has been put forward (Tresilian 1998), the avoidance response is a 'subtle' and 'precise' reaction to a particular layout of object and non-target object(s) in a workspace, then responses should be symmetrical across hand preferences and which hand (dominant or non-dominant) was used to perform the task.

(ii) Several studies have shown that there are asymmetries in performance between the dominant and non-dominant hand, where the dominant hand typically performed better in a manual aiming task than the non-dominant arm (Roy et al. 1994; Carson et al. 1993; Elliott et al. 1993; Sainburg and Schaefer 2004). Furthermore, there are numerous studies that have shown a right arm advantage in strength, speed and consistency of movement compared with the left arm in right-handers (for a review see Goble and Brown, 2008). In addition, skill-related differences between preferred and non-preferred hands have been observed in several domains. These include drawing lines (e.g., Woodworth 1899), finger tapping (e.g., Todor et al. 1982), precision-placing movements (e.g., Annett et al. 1979), reaching-to-point to a visual target (e.g., Elliott et al. 1993) and bimanual coordination (e.g., Buckingham and Carey 2009). The effects of motor lateralization might extend into the obstacle avoidance paradigm. To our knowledge, this has not yet been tested. An asymmetry in avoidance responses between the dominant and non-dominant hand would prohibit the generalization of right-handed avoidance responses by right-handers and place the findings concerning stronger ipsilateral effects in a new light.

We designed an experiment to test whether non-targets presented on the outside of the reaching hand cause more deviation irrespective of where they were located qua absolute position, the hand preference of the actor or which hand was used. Right- and left-handed participants were therefore asked to perform reach-to-grasp movements toward a physical object with a physical non-target present in the workspace. The target could be located ipsi- or contralaterally to the reaching hand. This means that during

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[1] Chapman and Goodale (2010) showed that avoidance responses were greater with one obstacle than with two obstacles. The fact that two obstacles were present in some studies means that the avoidance response in those cases might have been constrained. In bold strokes, the avoidance responses to a primary obstacle may have been smaller in order to properly avoid the secondary obstacle. We consider that although the magnitude of the avoidance response may have been smaller with two obstacles present the direction of the effect is still quite systematic, in that ipsilateral obstacles still evoke a stronger response than contralateral obstacles.

reaches, the elbow joint could cross the midline of the workspace (e.g., right hand was moved toward left target) or stay on one side of the workspace (e.g., left hand was moved toward left target), leading to crossed and uncrossed reaches, respectively. The non-targets could be on the inside or outside of the hand when it moved to the target. Reaches were performed using either the right or left hand.

Methods

Participants

Twenty participants (6 men and 14 women) volunteered to take part in this study and were all between the ages of 19 and 28 years old ($M = 22.0$, SD = 2.03) and had normal or corrected-to-normal vision. Half the participants were right-handed, while the other half were left-handed. All participants volunteered to participate in exchange for a small fee or curricular credit and gave their informed consent. The faculty's institutional review board under the Medical Research Act issued a formal written waiver that this research project did not require approval from a Medical Ethics Review Committee.

Apparatus and stimuli

The participants were seated at a white table (610 mm × 1,220 mm). The table had a workspace of 400 mm × 400 mm in which participants were asked to perform the experimental task. Three buttons were present in the table: one start button, located in front of the participant, along the midline of the workspace and two 'target' buttons that were in fact triggers that responded to a target being lifted from them. The target locations were both at a distance of 400 mm from the start button, one at an angle of 15° with respect to the midline, while the other was at a −15° angle (see Fig. 1). Wooden cylinders (150 mm height ×50 mm diameter) were used as target objects and as non-target objects.

All non-targets were placed at a distance of 300 mm from the start button. The center of the right non-target was placed at an angle of 30° with respect to the midline of the workspace (a further 15° beyond the direction of the right target location). Similarly, the center of the left non-target was placed at an angle of −30° (see Fig. 1). The central non-target was located at an angle of 0° with respect to the midline of the workspace (the center of this non-target was straight ahead of the start button). Note that the non-targets in this experiment were all at the same distance from the start button, viz. 300 mm.

Participants wore PLATO LCD goggles (Translucent Technologies, Toronto, Canada) and MiniBird magnetic markers (Ascension Technology Corporation, Burlington, USA), which permitted, respectively, manipulation of visual feedback and kinematic tracking with a sampling rate of 100 Hz over 3 s. The tracking markers were placed at the tips of participants' right index finger and thumb to measure their positions with .1 mm accuracy. These locations have been reported earlier as sites for markers (e.g. Mon-Williams and McIntosh 2000) and are considered to be the focus of prehension research (Ansuini et al. 2007). Care was taken to avoid situations in which the width of the marker itself interfered with the movement. The cables were fixed to the participants arm as well as to the edge of the table with tape and elastic, so that participants could move their hands and arms without restriction.

Design

Left-handed and right-handed participants performed both control and experimental trials with their preferred and non-preferred hands. The control trials served as a baseline for normal reaching behavior for comparison with the experimental trials. The control trials consisted of reaches toward both target locations with either the left or the right hand, i.e., crossed and an uncrossed reaches dependent on target location and which hand was used. During the control trials, a non-target was never present. During the experimental trials, a single non-target was present. For each experimental trial, there were 2 possible non-target locations on the inside and outside of the reaching hand. There were 4 control conditions [hand used (left, right) × target location (left, right)] and 8 experimental conditions [hand used (left, right) × target location (left, right) × non-target location (inside, outside)]. All conditions were presented eight times, which makes a grand total of ($12 \times 8 = 96$) trials excluding the practice trials.

The left- and right-handed participants were randomly divided into one of two groups, starting the first block of trials with either their left or their right hand. Each group was counterbalanced so that it contained an equal number of left- and right-handed participants. The experiment was divided into four blocks: two blocks for each hand used. After the second block, the experimenter changed the markers to the other hand. In each block, all conditions for that hand were presented twice ($2 \times 12 = 24$ trials per block). The sequence in which the trials were presented in each block was randomized.

Procedure

At the beginning of a block, the participants were instructed to begin their movements with a particular hand. The chair and the MiniBird markers would be placed accordingly. The participants were then given the instruction to start the

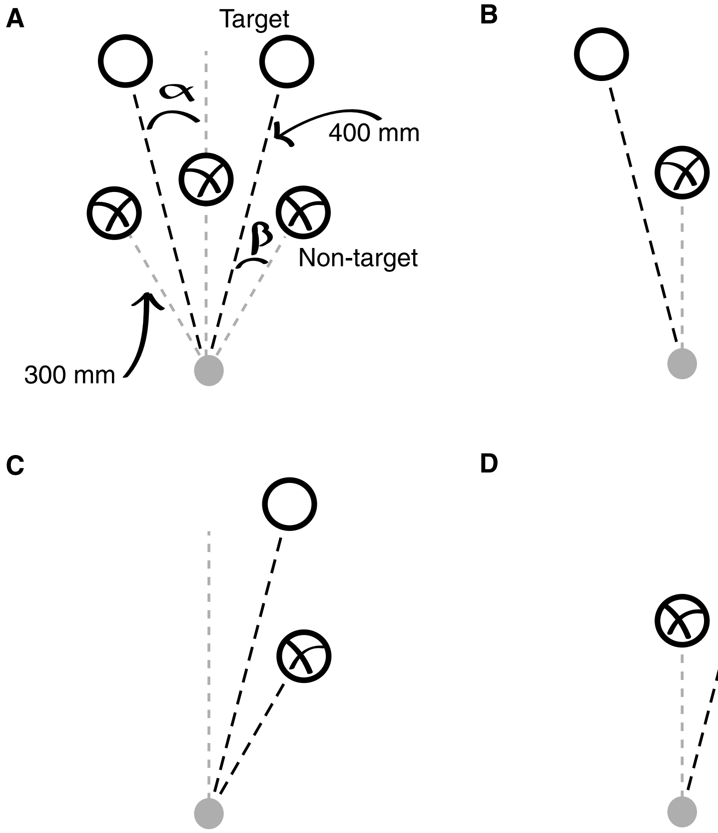

Fig. 1 *Top down* view of possible layouts of the experimental workspace. **a** The possible target locations and possible non-target locations. The *gray filled circle* represents the starting location of the hand. The *blank circles* represent targets. The *crossed circles* are possible non-targets. The targets were always located at a depth of 400 mm from the starting location, whereas non-targets were positioned at a depth of 300 mm. The angle $\alpha = 15°$ represents the angle between the *vertical midline* and the direction of the target. This angle (α) could be *negative* or *positive*, leading to targets to the *left* and *right* of the midline, respectively. The angle $\beta = \alpha = 15°$ is the angle between the direction from the starting position toward the target and the direction from the starting position to the non-target. Once again, the sign of the angle, in this case: β, determined whether a non-target was more to the right (*positive* β) or to the left (*negative* β) in the workspace than the target. The angles α and β and the hand that were used determined the type of trial that was performed by the participant. To illustrate, if a right hand was used to perform the reaches to a target, then the above *panels* show a contralateral target with an outside non-target (**b**), an ipsilateral target with an outside non-target (**c**) and an ipsilateral target with a non-target on the inside of the reaching arm (**d**). If, on the contrary, a left-handed reach was performed with these setups, then these *panels* would represent an ipsilateral target with a non-target on the inside of the reaching arm, a contralateral target with an inside non-target and a contralateral target with an outside non-target

movement as fast as possible after hearing an auditory cue and to smoothly reach and grasp the target object without touching the possible non-target. We instructed participants to grasp the target with thumb and index finger halfway along its vertical axis. This particular constraint at the end of the movement combined with both the movement constraints offered by the obstacles and the starting posture was used in order to increase behavioral consistency. This way the most direct trajectory to the target never went over the top of the obstacle or passed the inside of the obstacle when it should have gone passed the outside or vice versa.

Before each odd-numbered block, participants first went through six practice trials in which only a target object, either on the left or on the right target location, was presented.

Before each trial, the experimenter prepared the relevant condition by placing the target object and non-target on the workspace. Upon completion of the setup, the experimenter would cause the goggles to open. The participant was then granted vision of the workspace for a short time (800–1,200 ms) before an auditory signal cued them to perform the task. Next, the participant had to reach toward, grasp and lift the target object with their thumb and index finger and then put it back on the target location. Upon task completion, the participant used their index finger to press the start button. This closed the PLATO goggles and ended the trial. After pressing of the start button, participants were required to hold their fingers at that location while awaiting the next trial.

Dependent measures and analysis

The raw trajectory data of trial were filtered by using a dual low-pass second-order Butterworth filter with a cut-off frequency of 20 Hz (see also: Mon-Williams et al. 2001; Tresilian et al. 2005). The filtered trajectory data were then normalized using a cubic spline interpolation into 100 samples (see also: Smeets and Brenner 1995; Tresilian et al. 2005).

Using the position data and stimulus presentation data, the following measures were computed:[2] reaction time (response latency after the auditory cue until movement initiation), movement time (the time it took from the start of the movement until the end of the reach-to-grasp movement), grip aperture (three-dimensional distance between thumb and index finger markers), peak velocity (the maximum velocity attained during movement), time to peak velocity (time since the start of the movement until peak velocity was reached) and deviation at passing (horizontal position at the moment the hand passed the vertical position of the middle of the target). For all measures, difference scores were computed between the experimental condition and the relevant control condition (i.e., only movements with the same hand toward the same target were compared thusly) per condition and per participant.

Trials were rejected if the reach was initiated before the starting cue was given, the reach did not end within the recording window (3 s), or because of unforeseen recording errors. Three participants were rejected because at least 10 % of their trials were excluded from further analysis.

Results

We performed an initial mixed model repeated-measures ANOVA with a between subjects factor *handedness* (2 levels: left and right) and within-subject factors *hand used* (2 levels: left and right), *target location* (2 levels: crossed and uncrossed), and *non-target location* (2 levels: inside and outside of the reaching arm). Our analysis showed no significant difference between left-handed and right-handed individuals, nor any significant interaction effects which involved the factor handedness, for all dependent measures (all p's > .05). Therefore, handedness data were collapsed as follows: first, to test for a difference between the use of the preferred and non-preferred hands, it was necessary to 'mirror conditions.' For example, a movement trajectory around a non-target toward a target such as depicted in Panel B of Fig. 1 is quite different when either the right or left hand was used. In this case, a comparison between hands used with the 'same' setup would be a false comparison. To compensate for this, we took reaches that had the same relative setup and took the mirror image of one through horizontal mirroring. To illustrate, a reach with the right hand in a situation as depicted Panel B should be compared with a left-handed reach as in a setup as depicted in Panel D, after mirroring was complete. During this mirroring procedure, all conditions were projected to the right side of the workspace to ease the meaningful comparison. Second, the factors, hand used (left and right) and handedness (left-handed and right-handed), were collapsed into preferred and non-preferred, so that non-preferred and preferred handed reaches could be analyzed per non-target location. Please note, therefore, that in the following analyses, hand used no longer refers to left or right hand as it did in the design section, but now refers to the fact whether participants used their preferred or non-preferred hand to perform the experimental task.

We analyzed all subsequent measures with a within-subject analysis, viz. a repeated-measure ANOVA with the within-subjects factors described in the above. Where descriptive statistics are reported, '±' always refers to ±1 standard error of the mean.

Deviation at passing

There was no main effect for hand used, such that mean deviation at passing in the conditions where the dominant hand was used was not significantly different from mean deviation at passing in the conditions where the non-dominant hand was used. Right-handed and left-handed participants did not move their index finger along different trajectories toward the target during similar conditions, e.g., a reach toward an ipsilateral target with an outside non-target. This similarity between right-handers' and left-handers' movements is further illustrated in Fig. 2, which shows the mirrored nature of index finger trajectories made by right-handed and left-handed individuals.

A main effect was, however, found for non-target location, $F_{(1, 16)} = 174$, $p < .001$. The mean deviation at passing for outside non-targets was −29.2 mm (±2.03), and for inside non-targets, it was 1.54 mm (±1.04), which indicates that participants strongly deviated away from the outside non-targets but did not do so for inside non-targets (see also Fig. 3). To increase support for this, we statistically tested 'inside' conditions with the reference value of the control condition (0). This showed that 'inside' conditions taken together did not significantly depart from the relevant

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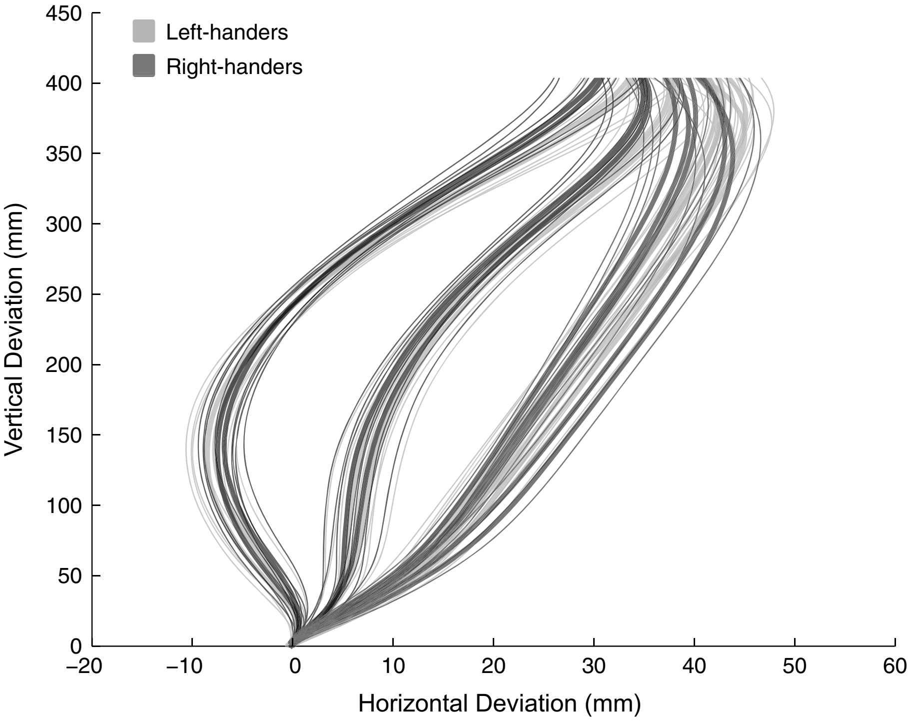
[2] Unless specifically stated, otherwise all measures were computed from index finger marker data.

Fig. 2 Trajectories for all conditions of left-handers and right-handers. Mean trajectories for all experimental conditions for left-handers (*thick gray lines*) and right-handers (*thick black lines*). The *thin lines* depict standard error of the mean across subjects per group. All reaches were standardized to a straight reach for a target. Please note that only the index finger data are plotted, which means that the trajectories are skewed because the index finger always ended up on the 'outside' of the target (right side for right-handed reaches and left side for left-handed reaches). In addition, to ease comparison between conditions, all trajectories have been rotated and the left-handed trajectories mirrored to resemble a straight reach forwards with the right hand



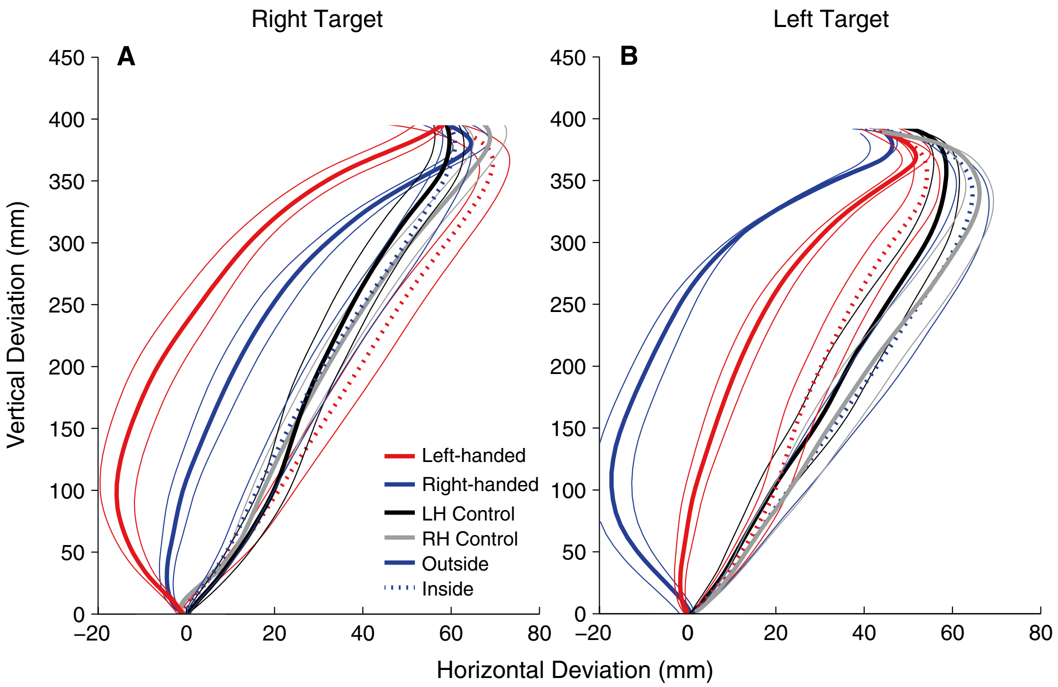


Fig. 3 Mean trajectories toward the left and right target. Mean movement trajectories across participants in the x, y plane. The *thick lines* indicate average trajectories in the experimental and control conditions. The *thin lines* represent movement error around those trajectories, specifically: between subjects error using the between subjects error correction for repeated measures as proposed by Cousineau (2005) for use in figures. Please note that only the index finger data are plotted, which means that the trajectories are skewed because the index finger always ended up on the 'outside' of the target (right side for right-handed reaches and left side for left-handed reaches). The hand dominance conditions (dominant and non-dominant) were collapsed. *Color* was used to denote whether right-handed (*blue* and *gray*) or left-handed reaches (*red* and *black*) were performed. *Solid lines* represent reaches with outside non-targets present, while *dotted lines* show reaches with non-targets on the inside of the reaching arm. **a** Depicts reaches toward the right target, and **b** shows reaches toward the left target

control condition, $p = .17$, whereas the difference between 'outside' conditions and the relevant control condition reached significance, $t_{(16)} = -14.3$, $p < .001$. This implies that participants deviated from the 'normal' path to the target when the non-target was on the outside, while in the 'inside' conditions, participants' hand trajectories did not deviate at all from the control condition. Although reported only once here, this is true for all subsequent measures as well. Because we find no significant departures from the control conditions for any 'inside' non-target conditions, we postulated that no deviation toward inside non-targets occurred in this experiment.

Another main effect was determined for target location, $F_{(1, 16)} = 43.6$, $p < .001$. The mean deviation at passing for uncrossed targets was −10.4 mm (±1.21), and for crossed targets, it was −17.3 mm (±1.26), which indicates that participants generally deviated more away from the non-targets when performing crossed reaches to targets than during uncrossed reaches to target objects.

There was an interaction effect for target location with non-target location, $F_{(1, 16)} = 75.6$, $p < .001$. Further investigation using Bonferroni-corrected t-tests revealed that when the non-target was on the outside of the reaching arm, it interfered differently with reaches toward the target requiring a crossed reach than the target requiring an uncrossed reach, $t_{(16)} = -12.4$, $p < .001$, whereas non-targets on the inside of the reaching arm did not differentially interfere with crossed and uncrossed reaches, $t_{(16)} = -.62$, $p = .54$. A crossed reach to a target with an outside non-target had a mean deviation at passing of −40.2 mm (±2.29), whereas an uncrossed reach in the same situation had an associated deviation at passing of −35.8 mm (±2.28). This indicates that participants deviated more strongly from outside non-targets when performing crossed reaches (see also Fig. 4). No other interactions were significant.

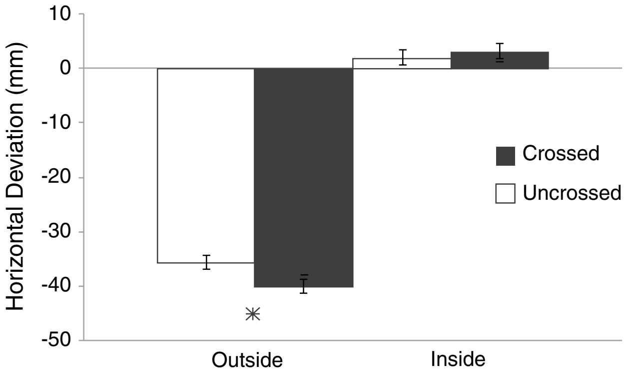


Fig. 4 Detailed interaction effect. Mean deviation at passing for crossed and uncrossed reaches when non-targets were on the outside or inside of the reaching arm. *Black bars* depict crossed reaches, while *white bars* depict uncrossed reaches. The *asterisk* shows significance at the $p < .001$ level. *Error bars* are standard error of the mean and the between subjects error correction for repeated measures as proposed by Cousineau (2005) for use in figures was applied

Reaction time

We found no significant differences between conditions for reaction time.

Movement time

We found no significant differences between conditions for movement time.

Grip aperture

We found no significant differences between experimental conditions for grip aperture. This suggests that participants had a consistent grip aperture during the experiment and that they did not vary their grip aperture systematically as part of an avoidance response. This means that the deviation measures reported earlier (and measured using the index finger marker) are not confounded by grip aperture responses.

Peak velocity

A main effect of target location was determined, $F_{(1, 16)} = 25.7$, $p < .001$. The mean peak velocity for uncrossed reaches was 1,352 mm/ms (±45), and for crossed reaches, it was 1,387 mm/ms (±44). Therefore, reaches that crossed the workspace were performed faster than uncrossed reaches.

A second main effect was found for non-target location, $F_{(1, 16)} = 5.87$, $p < .05$. The mean peak velocity for reaches with outside non-targets was 1,387 mm/ms (±55), and with inside non-targets, it was 1,362 mm/ms (±45). Taken together with movement time data and trajectory data, this implies that participants maintained a constant movement time by increasing speed during trials were the trajectory veered more away from the non-target (which by definition created a longer reaching path).

No further main effects or interaction effects were found.

Time to peak velocity

We found main effects of target location, $F_{(1, 16)} = 5.54$, $p < .05$, and non-target location, $F_{(1, 16)} = 7.58$, $p < .05$, on time to peak velocity. Peak velocity was reached significantly later for outside non-targets 51.5 % of movement time (±3.6) than for inside non-targets 19.2 % of movement time (±2.2). The mean time to peak velocity for uncrossed reaches was 38.3 % of movement time (±4.2)

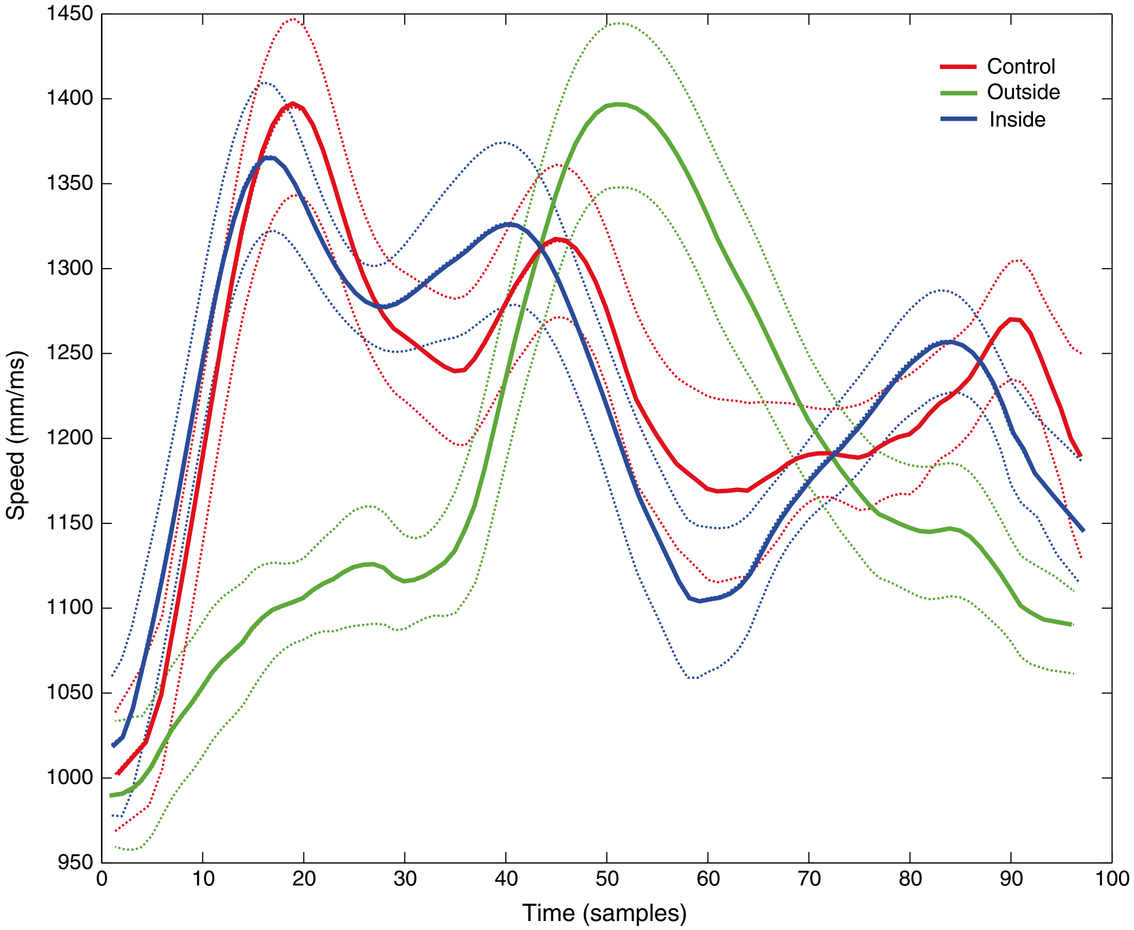


Fig. 5 Mean velocity profiles for inside and outside non-targets. Mean velocity profiles for inside (*blue*) and outside non-targets (*green*) as well as the control condition (*red*). Velocity on the *y*-axis and % movement time on the *x*-axis. The *solid lines* are means across participants, and the *dashed lines* are between subjects error [using the between subjects error correction for repeated measures as proposed by Cousineau (2005)]. Target location and hand used factors have been collapsed for this figure

while crossed reaches attained peak velocity at 41.7 % of movement time (±4.0).

A further interaction effect was found between factors target location and non-target location, $F_{(1,\,16)} = 10.0$, $p < .01$. Mean time to peak velocity was 53.2 % of movement time (±5.0) for reaches in conditions with outside non-targets when reaching across the midline and 46.2 % of movement time (±5.4) for conditions requiring uncrossed reaching. Post hoc testing confirmed that outside non-targets elicited reaching peak velocity significantly later in the movement with crossed reaching vs. uncrossed reaching, $t_{(16)} = 2.31$, $p < .05$. The difference between crossed and uncrossed reaches with inside non-targets was not statistically significant, $p > .05$.

For both peak velocity and time to peak velocity, an effect of non-target location was found. As can be seen in Fig. 5, this effect is most likely due to different behavioral strategies by participants regarding moving speed in response to inside and outside non-targets. That is, if non-targets are on the outside of the reaching hand, the velocity of the hand is initially slower to around the point where the hand passes the obstacle when it quickly accelerates to a higher peak velocity compared to conditions with inside non-targets.

Discussion

The current study was designed to determine the cause of stronger ipsilateral non-target effects on reaching movements. As possible modulators of the reaching trajectory toward targets with ipsilateral non-targets, we considered handedness and non-target location and their possible interactions. To this end, we asked participants to perform reach-to-grasp actions toward a target object that could be at two different locations. These actions were performed with either the preferred or non-preferred hand by left-handers and right-handers. Another, non-target object was also present in the workspace, with exception of control trials which featured a single object. The additional non-target object could be on the inside or outside of the arm used to perform the reaches. We determined that handedness and hand used did not affect the kinematics of the reaching trajectories, whereas non-target location and target location did systematically affect trajectories toward the target. For the first time, we are able to unequivocally state that the observed trajectories in obstacle avoidance are the result of an interaction between limb position and non-target position. There seems to be no support for asymmetrical performance due to handedness or hand dominance in obstacle avoidance. This means that the effects that were found in earlier studies are not confounded by these latter factors and can be generalized across all possible positions in the workspace.

The main and interaction effects for target location can be explained by taking into account the type of movement that is performed. In our experiment, half the reaches were crossed, whereas the other half were uncrossed reaches. This means that either the right or left hand was transported from the starting position to the target that could be to the left or to the right of the starting position, so that right-hand-to-right-target and left-hand-to-left-target were uncrossed reaches and right-hand-to-left-target and left-hand-to-right-target were crossed reaches. The results indicated that crossed reaches, e.g., a reach with the left hand toward the right target, deviated more away from the non-target than uncrossed reaches, e.g., a reach with the left hand to the left target. Moreover, responses to non-targets were further increased when they were on the outside of the reaching hand as compared to the inside of the reaching hand. Biomechanical differences such as a larger displacement of the center of mass of the limb which could necessitate the recruitment of a different set of muscle groups for task execution might be responsible for larger deviations to trajectories of crossed reaches (compared to uncrossed reaches). The trajectory toward a crossed target would then possibly require the limb to move along a more curved path to maintain optimal control of the limb during transport (for a succinct description as to how the brain would organize this, see: Feldman and Levin 2009). The fact that these biomechanical considerations may play a role is supported by the interaction effect of target location with non-target location because non-targets that had to be avoided would cause the center of mass to be displaced even more during a crossed reach, which was the case. Thus, the larger deviations we reported for crossed reaches could reflect the optimal path vis-à-vis expended energy for the transported limb through the workspace toward the target without knocking the non-target over.

Our results further show that special attention should be paid to the situation where the non-target is on the outside of the reaching hand. Participants deviated more strongly away from the non-targets on the outside of the limb performing the reach than when the non-target was on the inside. The effect generated by the 'outsideness' of non-targets accounts for previous results regarding enhanced interference by non-targets that were on the right side of the workspace and generalize this to an effect of ipsilateral non-targets. This effect is independent of which limb is used or which side of the workspace the non-target is on. The same holds for non-targets on the left side of the workspace that were not associated with the hand veering away from the non-target during movements. Indeed, this null-effect can be generalized to all workspaces where contralateral or inside non-targets are present. Apparently, non-targets on the inside of the arm do not require a 'normal' movement to be modified in order to avoid it successfully. Therefore, we can confirm that only if non-targets actually interfere with the transport or grip phase of a movement toward a target, i.e., they obstruct the movement, then automatic alterations are incorporated into the movement so that it veers away from a non-target to avoid a collision (Tresilian 1998). The contralateral or 'inside' non-targets may have been beyond the safety margin for collision-free movement and therefore may not have required an avoidance response. In the case of an ipsilateral non-target that obstructs the lower arm, the observed trajectory might then be caused by a generated motor program to move along a path that skirted the non-target at the preferred distance, which –in all cases- would mean the hand would also move more away from the non-target when compared to a normal trajectory. This is precisely what we have found for 'outside' non-targets, irrespective of hand used or hand preference.

To account for the surprising absence of an asymmetry due to handedness or hand dominance which have been reported in many domains, we refer to Mutha, Haaland, and Sainburg(2013). Mutha et al. (2013) proposed a new view that motor lateralization or handedness is a reflection of the proficiency of the cerebral hemispheres for distinct movement control mechanisms. That is, each hemisphere has different control mechanisms for movements of its associated arm. However, each hemisphere has a different dominant control mechanism which suits the function the hand is engaged in and is expressed on a population level as handedness. Mutha et al. (2013) showed that right-handers using their dominant arm rely on predictive mechanisms regarding the dynamic properties of the arm to guide reaching direction and trajectory and that the reaching behavior of the non-dominant arm reflected optimal positional stability. This was done by occasionally and covertly shifting the start positions of the reaching movement either collinearly or orthogonally to the required direction of movement. No effects of orthogonal shifts were found, whereas collinear shifts had a differentiated effect on reaching movements: the dominant arm maintained the direction and straightness of the trajectory, while the non-dominant arm deviated to the previously learned goal position. This led the investigators to propose that two control mechanisms coexist in the brain and are, although associated with a particular hemisphere, independent of the effector. Following this, if obstacle avoidance is the ability to smoothly guide the hand around obstacles, which relies on the predictive control mechanism based on arm and hand dynamics and if this control mechanism is not specific for a particular arm, then obstacles are avoided similarly with the dominant and non-dominant arm and avoided similarly by right-handers and left-handers. Therefore, only the positioning of the target and obstacle should have an effect on the movement direction and movement trajectories. Our results support the notion that an identical control mechanism is selected for both arms independent of the actor's handedness. However, it could also be said that our task specifically—or obstacle avoidance in general—may have not been difficult enough to evoke differentiated responses from the trajectory controllers of the dominant and non-dominant hemispheres.

To reconcile, the relative position of a non-target with respect to the limb and its future path dictates the subtle and precise response of the motor system as to keep a preferred distance between the acting limb and the non-target. This process is not severely biased by which hand is used, the hand preference of the actor or the fact that hand and non-target are on the same side of space. It is influenced strongly, however, by the type of movement that is required (e.g., crossed or uncrossed) and the relative position of non-targets. Any effects previously described in literature concerning non-targets near the right hand are therefore generalizable to all non-targets on the outside of the reaching hand.

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